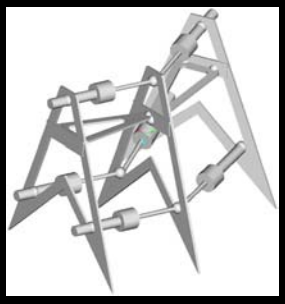
Autonomous design and fabrication for long term space exploration



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Exploration cycle is too long

- Years to design and fabricate a robot
- Long one-way trip
- Several cycles necessary
- Not every cycle successful
- Can't do them concurrently
- A decade or two for distant planets

How can we shorten the cycle time?
Most approaches have focused on faster travel

The StarTrek "replicator" approach Phase I

- Send over a replicator (Once, all planets)
- Beam over a general probing robot
- Sense the environment, send info back
- Redesign, beam over the next, more specific robot, etc.
- Recycle robots and extend the replicator
- Design & test cycle reduced from decades to months

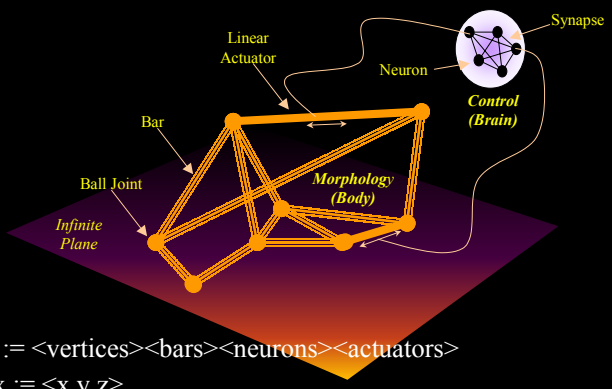
The StarTrek "replicator" approach Phase II

- Close the loop by local autonomous design
- Humans control high level requirements
- Design & test cycles performed locally
- Recycle robots and extend the replicator
- Design cycle reduced even further

Components of a system

- Design space
  - Founding building blocks
  - Rules
  - Feedback mechanisms
- Physics
  - Simulator
  - Real testing
- Open ended design automation
  - Self organizing systems like evolution
- Extremely flexible fabrication system
  - Layered manufacturing

The Design Space

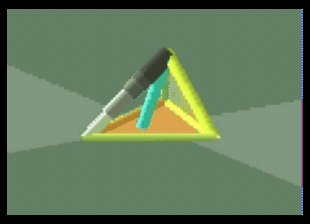


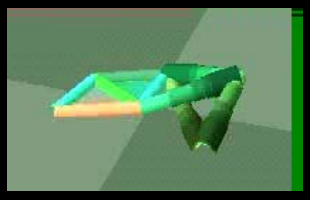
- robot := <vertices><bars><neurons><actuators>
- vertex := <x,y,z>
- bar := <vertex1 index, vertex2 index, relaxed length, stiffness>
- neuron := <threshold, synapse coefficients of connections to all neurons>
- actuator := <bar index, neuron index, bar range>

Evolving for Locomotion

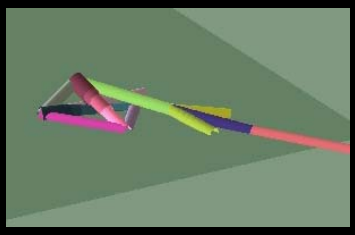
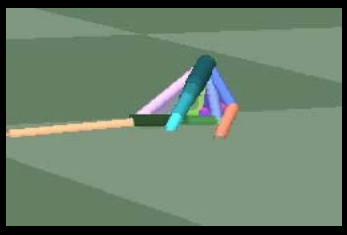
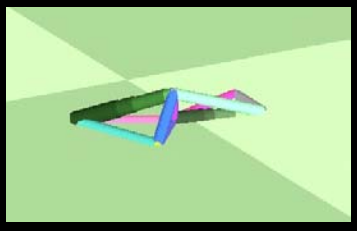
- **Population**: Starts with empty/null designs. Size 200 ~ 1000 machines
- **Genotype/phenotype:** bars/actuators, and neurons
- **Fitness function**: distance center of mass moved during 12 cycles of the neural net
- **Selection function**: fitness proportionate, rank, random
- **Genetic operators**: small mutations:
  - Connect/remove small bar or unconnected neuron
  - Change bar length or neuron synapse
  - Split bar/vertex
  - Connect/disconnect neuron to bar (actuator)
- **Replacement function**: random, crowding, elitism.
- **Evolution dynamics**: Steady state 100 ~ 10000 generations. Various dynamics of convergence and divergence. Parallel implementation yields "natural evolution" drive for simplicity:

Results





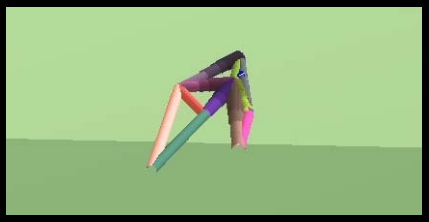
Results

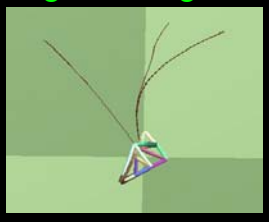

Other objectives

Lifting

Reaching



Light Seeking




Complete robot fabrication





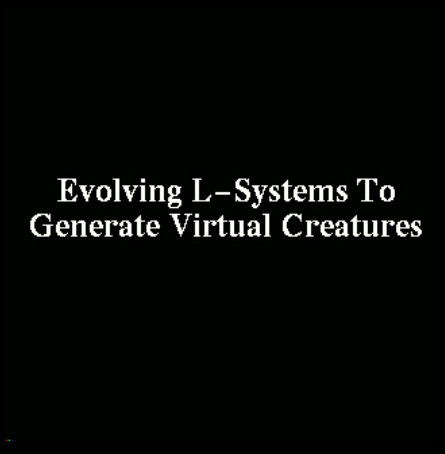
Automatically generated machines



Reaching higher complexities

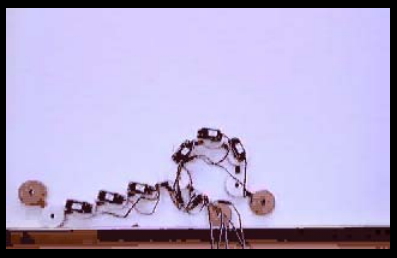
- Open-ended design problem exponentially intractable with low-level mutation-selection processes
- Need mechanisms that discover and use
  - Modularity
  - Regularity
  - Hierarchy
  - Abstraction

More complex machines



More complex machines

- Genotypes that encode a model for a developmental process
- DNA, Graph growing, L-Systems*



*With Greg Hornby, Brandeis CS

Research questions and Technological Challenges

- Flexible and fully autonomous fabrication
  - Multi functional 3D printing
  - Self-extension (self-replication?)
  - Recycling, then,
  - Using local energy/material resources
- Open ended and fully autonomous design
  - Reaching higher complexities
  - Physical feedback cycle

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for long term space exploration

Lipson and Pollack (2000), *Nature 406*